Post-fracture behaviour of laminated plates after human impact test

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ABSTRACT: For safety barriers the load bearing capacity of the glass when subjected to the soft body impact should be verified. The soft body pendulum test became a testing standard to classify safety glass plates. The classification of the safety glass do not consider the structural behavior when one sheet of a laminated glass is broken; in situations when the replacement of the plate could not be very urgent, structural behavior should be evaluated. The main objective of this paper is to present the structural behavior o laminated glass plates, though modal test and human impact test, including the post fracture behavior for the laminated cases. A god reproducibility and repeatability is obtained. Two main aspects of the structural behavior can be observed: the increment of the rupture load for laminated plates after the failure of the first sheet, and some similarities with a tempered monolithic behavior of equivalent thickness.

1 INTRODUCTION

Human impact is a dynamic load that should be taken into account for the design of the glass panels located on some identified risk areas. In these areas, building codes require the use of a safety glass which performance and classification is evaluated with the impact pendulum of UNE-EN 12600.

The classification of the safety glass do not consider the structural behavior when one sheet of a laminated glass is broken; in situations when the replacement of the plate could not be very urgent structural behavior should be evaluated.

For safety barriers the load bearing capacity of the glass when subjected to the impact of a soft body should be verified. After many research done with the study of human impact on safety glazing, the soft body pendulum test became a testing standard, UNE-EN 12600. It has been of great interest for researchers in the last ten years the study of soft impact and the simulation of the behaviour of monolithic and laminated glass, with different boundary conditions (Schneider & Schula 2010, Schneider & Wörmer 2001, Du Bois et al. 2003). Large experimental programs to better understand the impact behaviour were performed at the Universidad Politécnica de Madrid; these results are used for this work (Pacios et al. 2011, Postigo et al. 2011).The technical procedure TRAV regulates the verification and application of glass panes with soft body impacts.

The main objective of this paper is to present the structural behavior o laminated glass plate, though several dynamic test, modal test and human impact test, including the post fracture behavior for the laminated cases.

2 EXPERIMENTAL PROGRAM

The experimental program was designed to obtain the impact results in glass plates before and after one of the sheets breaks, in order to better understand their integrity.

The experimental results used in this paper were obtained, using an impact pendulum designed following the UNE-EN 12600, to test glass plates of different thicknesses and support conditions, equivalent to those currently used in structural glazing construction (Postigo et al. 2007). Seventeen test specimens were subjected to a total of 240 impacts (including 2 or 3 impacts for each condition) with initial drop heights ranging from 25 mm to 1,200 mm (low and high energy impact levels). The repeatability of the test was very good and, thus, many results overlap (Postigo et al. 2011).

At the beginning and end of the test series, the frame was checked in order to ensure compliance with the requirements standard, which demands that the values of the vertical and horizontal micro-strains for monolithic glass plate with a 10 mm thickness, fall within a given range of values.

The instrumentation used in the impact tests was:

- Accelerometers Accel 1 and 2 for control of the frame, Accel 3 for control of the glass plate, and Accel 4 to record the acceleration of the pendulum; ± 20,000 g (0.1-12,500 Hz).
- Strain gages: to register the horizontal and vertical micro-strains in the center of the rear surface of the glass plate during impact. Gage length of 5 mm, a gage factor of 2.03 and a resolution of 2 micro-strains. Horizontal strain gage is located on the middle horizontal line, and the vertical strain gage is located in the middle vertical line 15 mm below the horizontal line.
- LVDT for the registration of the pendulum height during different stages of impact ±50 mm range and an accuracy < ±0.11%.

Two different types of tests have been performed on every glass plate: modal test for the identification of the structure with the transfer function, natural frequencies and point modal stiffness, and human (soft) impact test for the dynamic load application.

As it was mentioned before, the testing program was designed to study variations in glass type, boundary conditions, thickness, dimensions and typology of the glass plates. All of the variations were selected to facilitate studying current glazing solutions: four-sides supported (4S), two-sides supported (2S), four-pin-point supported (4P), thicknesses (5, 3+3, 4+4, 5+5, and 10 mm), annealed laminated (L) and tempered monolithic glasses (T).

Table 1 shows the results used for the work presented here. Only laminated glasses are considered for this study, and glazing solution with four-sides supported (4S). Three groups of laminated glass, with a double layer of annealed glass of 3mm, 4mm, and 5mm of thickness and PVB interlayer (L33, L44, L55), were tested under human impact test. Also, the natural frequency and the apparent stiffness on the middle of the plate, for the first mode, have been measured for all the specimens.

Table 1. Experimental program.

	Dimensions (mm x mm)	Number of Impacts	Number of heights	Modals Free-free	Modals Operational
L55-4S	876 x 1938	51	14	4	34
L44-4S	876 x 1938	17	8	4	11
L33-4S	876 x 1938	37	13	4	13

Figure 1 shows the pictures taken after two impacts for the same glass plate, L55B, at different impacts heights. At 201 mm the traction glass layer broke; however it was possible to perform impact tests until the height of 801 mm were both layers broke. We use *degradation condition* for plates with the traction layer broken, and *total fracture condition* for plates with both layers broken. All data were registered, even though results from strain gages are not valid after degradation.

Degradation, height 201 mm | Total fracture, height 801 mm

Figure 1. Glass degradation and glass total fracture for L55B.

Table 2 resumes the number of impacts before degradation and before total fracture. It was still possible to continue testing the plates, since there was residual load bearing capacity. For the laminated glass plates of higher thickness almost the double of number of impacts was needed before total fracture of the glazing.

Table 2. Number of impacts before and after degradation for every specimen.

Name	No. plates	No. impacts before		No. Heights	Measured Height (mm)	Maximum Nominal Height (mm)	
		Degradation	Total fracture				
	B	3	11	1	200		
L55-4S	C	0	7	0	--	190	200
	D	3	26	1	200		
	B	3	8	1	35		
L44-4S	C	1	1	1	55	25	50
	D	2	1	1	50		
L33-4S	C	6	5	4*	34 - 100	75	150
	D	18	8	6*	34 - 160		

*Important differences between glass C and D due to the small impact height.
L55B, L44B and L33D are the specimens selected to show the results.

Table 3. Height for degradation a total fracture of the specimens.

Glass		Specimen B	Specimen C	Specimen D
L55	Degradation (mm)	200	190	250
	Total fracture (mm)	800	1200	1200
L44	Degradation (mm)	50	100	-
	Total fracture (mm)	150	-	190
L33	Degradation (mm)	-	100	175
	Total fracture (mm)	-	300	450

Table 3 presents the height when the first plate breaks, *degradation* state, and the height when the second plate breaks, *total fracture* stage. Even thought repeatability and reproducibility for impact test is very high (Postigo et al. 2011)) not all the specimens give the same answer.

3 EXPERIMENTAL RESULTS

From all the variables that were registered during the impact, only pendulum acceleration is considered in this paper, since is the one that better represents the impact phenomenon. The three graphs plotted in Figure 2, represent the pendulum acceleration of three different samples of the same type of glass, L55, that are impacted at the same height of 199 mm. Specimens B and D resists the impact, while one plate of the laminated glass breaks, for specimen C. Considering the low energy of the impact for a specimen of equivalent thickness of 10 mm, one may think that none of the glass plates should have broke; However this is in agreement with the probability of fracture determined by many authors.

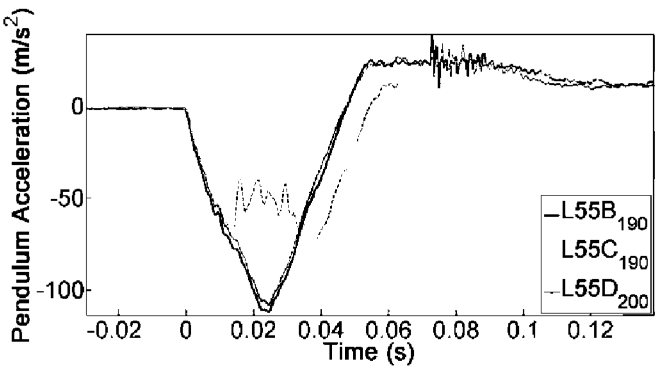

Figure 2. Acceleration of the pendulum for the height of 191 mm.

Tables 4 and 5 collect the experimental results for L33D and L55B. The data collected on the tables correspond with the main results of the instrumentation presented in paragraph 2. The nominal impact height (h), the initial (h_0) and final (h_1) pendulum height are measured with the LVDT. The maximum pendulum acceleration and the duration of the impact are measured with Accel 4. And the maximum micro-strains on transversal (ε_x) and longitudinal (ε_y) directions, are measured with strain gages. For general impacts, the differences between h_0 and h_1, due to the energy transmitted to the glass and dissipated during the phenomena, are around the 20%. For impacts with degradation, differences are higher than 50%, as can be seen on L33D for h=175 mm and L55B for h= 201 mm. Data between brackets corresponds with some incidences on the test.

A god repeatability is observed with the results of three test for each height. Incrementing the height it can be seen that the traction plate brakes, thus invalidating the strain data registers; however the glass specimens has the capability of resists impacts with higher energy. With the first breakage, the laminated glass properties change, but it maintains a structural behaviour, repeating robust results while repeating the test. Besides, it would be expected that the compression ply would break after damage, for impacts with smaller initial pendulum height. Its capacity to support impacts appears to be multiplied even almost by four.For L33D the total fracture occurs at 450 mm and for L55B is at 800 mm.

3.1 *Behavior before degradation*

To better understand the phenomena we show the pendulum acceleration for specimens L33D and L55B. Figure 3 shows the temporary registers for a sound glass plate L33; the shape of the curve is consistent with an integral structure. All plates tested with four-side support, either tempered or laminated glass plates, have similar behavior.

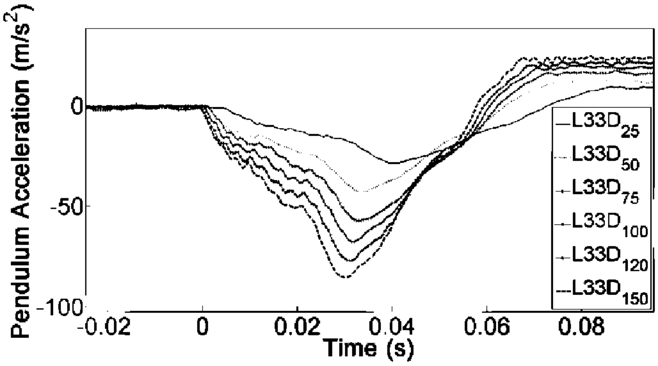

Figure 3. Pendulum acceleration for L33D before degradation.

Table 4. Experimental results for specimen L33D.

h (mm)	h_0 (mm)	h_1 (mm)	t (ms)	Acceleration$_{max}$ pendulum (m/s^2)	$\varepsilon_{max,\,x}$	$\varepsilon_{max,\,y}$
25	34.8	29.6	NUL	NUL	878.0	390.5
25	34.2	28.6	68.1	28.43	850.0	381.2
25	34.5	29	67.8	28.58	853.0	385.0
50	54.6	44.2	64.2	42.65	1112.0	509.0
50	54.8	44.1	64.3	42.40	1122.0	513.0
50	[56]	[43.3]	64.0	[40.64]	[1079]	[501]
75	82.3	66.5	61.2	57.1	1341	633.5
75	81.9	66.1	61.9	56.1	1322	626.5
75	81.9	65.9	62.1	56.5	1318	627.0
100	107.7	85.1	60.6	67.5	1462	711.0
100	107.4	85.1	60.4	67.7	1464	712.0
100	107.5	85.1	60.5	67.5	1466	710.0
125	134	102.3	59.6	77.1	1562	777.0
125	134.3	103.1	59.5	76.5	1563	780.0
125	134.6	104.5	59.6	77.6	1582	786.0
150	161.0	126.5	58.4	85.4	1671	849
150	160.3	127.0	58.6	83.8	1651	843
150	160.3	126.0	58.5	85.6	1653	845
175	177.0	75.2	[63.8]	[54]	[1687]	[790]
175	178.5	131.9	67.2	90.1	[2080]	[561]
190	191.5	142.8	66.4	94.5	[2040]	[536]
200	201.0	150.6	65.9	98.7	[2007]	[529]
250	252.0	185.3	65.3	113.3	[1971]	[575]
300	302.0	218.5	63.9	124.5	[2055]	[595]
450	453.0	32.6	[22.4]	[80]	[2237	[655]
1200	1154.0	71.1	[102]	[60]	NUL	NUL

Table 5. Experimental results for specimen L55B.

h (mm)	h_0 (mm)	h_1 (mm)	t (ms)	Acceleration$_{max}$ pendulum (m/s^2)	$\varepsilon_{max,\,x}$	$\varepsilon_{max,\,y}$
191	192	148	47.9	112	1240	752
191	192	148.5	47.6	112.6	1232	759
191	192	146	48.2	111.8	1233	752
201	200.5	87.6	NUL	114.9	[1253]	[770]
202	201	151	NUL	NUL	NUL	[1239]
203	200.6	148.4	58.5	98.3	NUL	[1133]
301	301.6	221	56.1	124.4	NUL	[1263]
302	301.8	221	55.1	124.4	NUL	[1270]
303	301.4	220.5	55.6	124.5	NUL	[1271]
451	453.3	319.4	50.9	158.2	NUL	NUL
452	452	321.4	51.2	158.2	NUL	NUL
701	697	477.5	49	210.8	NUL	NUL
702	697.3	481.5	48.6	209.5	NUL	NUL
801	784	29.2	[22.2]	144.3	NUL	NUL

3.2 *Post fracture behavior*

Figure 4 shows the registers for degradated glass plates. The shape of the curve has change and this is better appreciated for stiffer plates as for example L55.

Figure 5 plots all the representative results; the black continuous line for sound plates, dashed lines when one ply fractures, and the rest for degradated plates. It can be seen that the degradation do not appears the first time that the acceleration level is achieved. Similar situation is produced for the total fracture.

The graph L55B$_{190}$ represents the response for a good plate; the maximum acceleration is reached at 25 ms. The graphs L55B$_{201}$ follows the previous plot very close until the traction monolithic plate breaks after the maximum acceleration. Next impact, represented for L55B$_{202}$, shows a degradated plate with lower stiffness: the change in the shape of the curve until maximum acceleration is a very good indication. L55B$_{801}$ represents when the intact monolithic plates breaks. For the rest it can be seen a good repeatability including the degradation situations (see L55B$_{451}$ and L55B$_{452}$ for example).

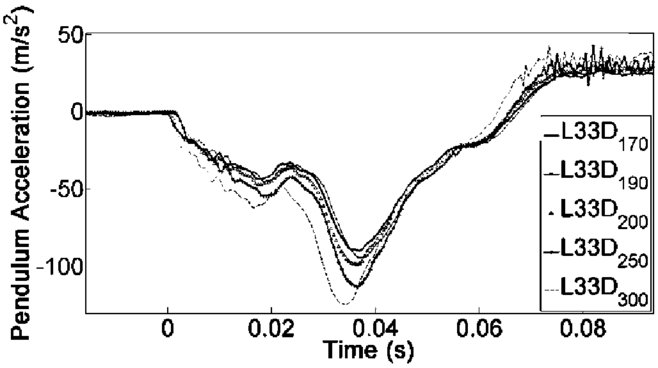

Figure 4. Pendulum acceleration for L33D after degradation.

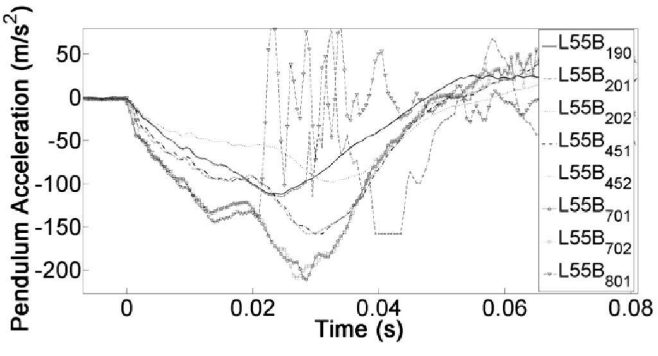

Figure 5. Pendulum acceleration for L55B before, during and after degradation.

Figure 6 shows the different Frequency Response Functions (FRF) obtained of the operational modal tests on the L55 before and after the breakage of the tensile ply. The first conclusion from these curves is the repeatability of the FRFs of the laminated glass partially degraded after the breakage, that supports the idea that the degradated plate is a "new structure" with a good dynamic behaviour.

From the registers it can be observed that the laminated glass plate, once degradaded, presents some similarities with the tempered glass plated with half the thickness (see Figure 7).

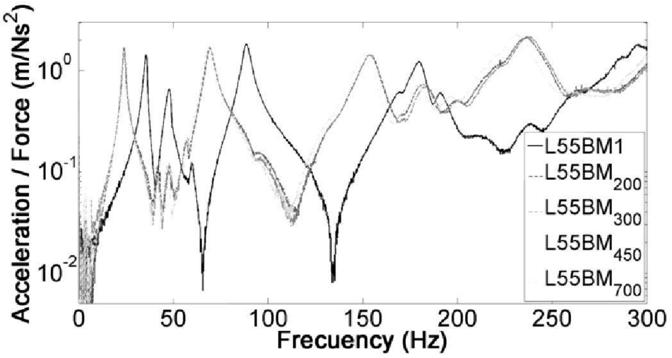

Figure 6. Frequency response function for sound and degradated specimens.

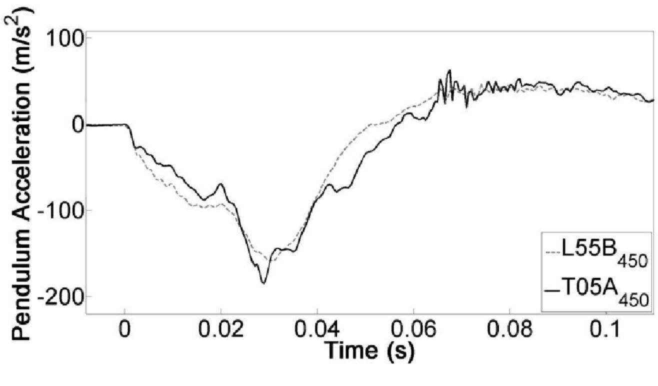

Figure 7. Comparison of pendulum acceleration between sound T05 and degradated L55.

4 CONCLUSIONS

The behaviour for human impact of laminated plates after degradation presents a good reproducibility and repeatability. Two main aspects of the structural behavior can be observed: the typical approach of monolithic behavior of laminated glass for human impact, and the increment of the rupture load for laminated plates after the failure of the first sheet.

The energy level needed to reach total fracture (breaking the second ply of the laminated glass) is up to four times higher to the energy level for degradation (fracture of the first ply).

Recent studies with numeric models from the same research groups point out that some apparent improvement of the fracture stress, due to the PVB layer that reduces the effect of superficial stress.

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